

Low-Voltage Standards in the 10 Hz to 1 MHz Range

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Abstract—A step-down procedure is described for establishing voltage standards in the 2 mV to 200 mV range at frequencies between 10 Hz and 1 MHz. The step-down employs low-voltage thermal voltage converters and micropotentiometers. Techniques are given for measuring input impedance and calculating loading errors.

Index Terms—Calibration, impedance measurement, micropotentiometer, thermal converters, voltage measurement

I. INTRODUCTION

A COMMONLY used method of generating millivolt-level signals is to convert a known current to a voltage using a micropotentiometer (μ pot) [1]. These devices were originally developed as low-voltage rf sources with relative uncertainties of around 1%. However, it has been shown that μ pots can be used to generate 2 mV to 200 mV signals from 10 Hz to 1 MHz with ac–dc differences ranging from 20 μ V/V to 1000 μ V/V [2]. Standards in this voltage and frequency range have been developed to support low-voltage thermal voltage converters (TVC's), μ pots, digital voltmeters (DVM's), digital multimeters (DMM's), and multifunction calibrators [3]–[6].

As the accuracy requirements of commercial instruments continue to improve, sources of error that were previously ignored become more critical. One such error source is the loading effect caused by the input impedance of devices connected to μ pots, which have nonzero source impedances.

II. STEP-DOWN PROCEDURE

Low-voltage ac standards are established at the National Institute of Standards and Technology (NIST) through a step-down procedure involving TVC's, μ pots, and resistive attenuators. The main reference is a 250 mV TVC that consists of a coaxially mounted single junction thermoelement (TE) with a heater resistance of 45 Ω . This TVC is calibrated at full scale against standard TVC's [2] and then used at 100 mV to calibrate a commercial multirange low-voltage TVC. A major assumption in the step-down procedure is that the ac–dc difference of the 250 mV TVC is the same at 100 mV as it is at full scale. Once characterized, the low-voltage TVC is used to calibrate a 100 mV μ pot at full scale. This μ pot is then used to calibrate the low-voltage TVC at 50 mV. The

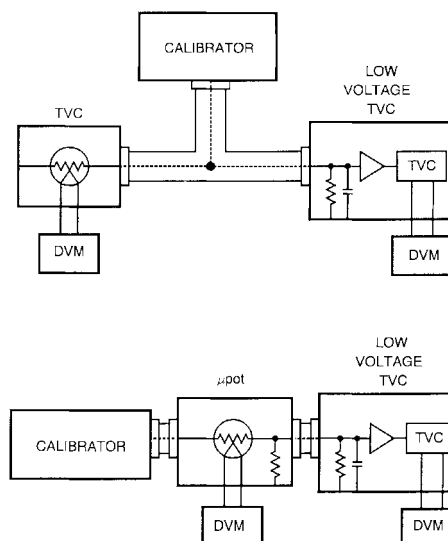


Fig. 1. Block diagram of the connections for comparing the low-voltage TVC to (top) the 250 mV TVC and to (bottom) the μ pot.

μ pots are based on single junction TE's, and it is also assumed that their ac–dc differences do not change significantly when operated at reduced current. This procedure, where each μ pot is calibrated at full scale and used near half scale to calibrate different ranges of the low-voltage TVC, is used to step-down to 2 mV. The two sets of connections are shown in Fig. 1.

To verify the above procedure, an alternate step-down method is employed which uses 50 Ω rf attenuator as an ac–dc transfer device. The signal voltage is characterized at 200 mV using the 250 mV TVC and then scaled using one or more resistive attenuators that reduce the voltage by factors of approximately 2, 4, 10, 20, 40, and 100. The connections for this test are shown in Fig. 2. The major assumption here is that the ac–dc differences of the attenuators are negligible in the dc to 1 MHz range.

III. LOADING ERRORS

The output resistance R_S of the μ pots and attenuators used in this step-down procedure may be as large as 50 Ω . To obtain the lowest measurement uncertainties, it is necessary to pay close attention to the input impedance of the low-voltage TVC. The input stage of this instrument is a wide-band operational amplifier that is used to amplify the input signal up to a level where it can be measured using a 2 V TVC. The input resistance of this amplifier is quite high at low frequencies; however, it decreases significantly as the frequency increases

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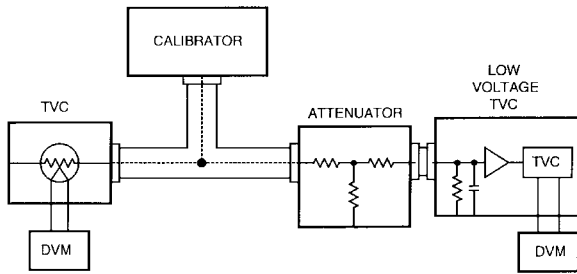


Fig. 2. Block diagram of the connections for scaling a characterized voltage using a resistive attenuator.

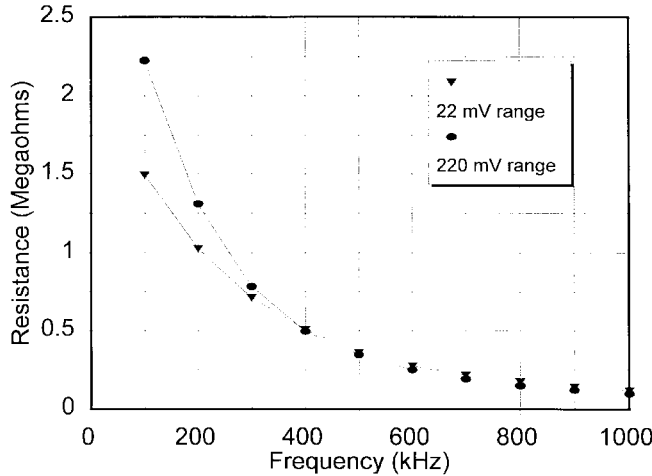


Fig. 3. The input resistance versus frequency of the two ranges of the low-voltage TVC.

above 100 kHz. Budovsky and Klonz¹ have shown that the input resistance of the low-voltage TVC may fall from 10 MΩ in the audio frequency range to less than 100 kΩ at 1 MHz. This change in input resistance will cause a change in the ac voltage delivered from a nonzero source impedance. It will not affect measurements made using the circuit in Fig. 1, top, since both TVC's see the same voltage. However, in the circuits shown in Fig. 1, bottom, and Fig. 2, the ac voltage supplied to the low-voltage TVC will decrease as the frequency increases.

Since the ac-dc difference measurement procedure for nonzero output resistance sources assumes that the TVC input impedance is constant with frequency, the calculated ac-dc difference must be corrected for this loading error. The input resistance R_I of the low-voltage TVC and the output resistance of the μ pot or attenuator are easily measured using an impedance meter (LCR meter). The resistances versus frequency of the 220 mV and 22 mV ranges of the low-voltage TVC's are shown plotted in Fig. 3. For a nonzero source resistance, the reduced input resistance causes a loading error that increases with frequency. If it is assumed that the input reactance has a negligible influence, the loading error E_1 is

$$E_1 = R_I / (R_I + R_S) - 1. \quad (1)$$

¹This information came through a private conversation with I. Budovsky and M. Klonz.

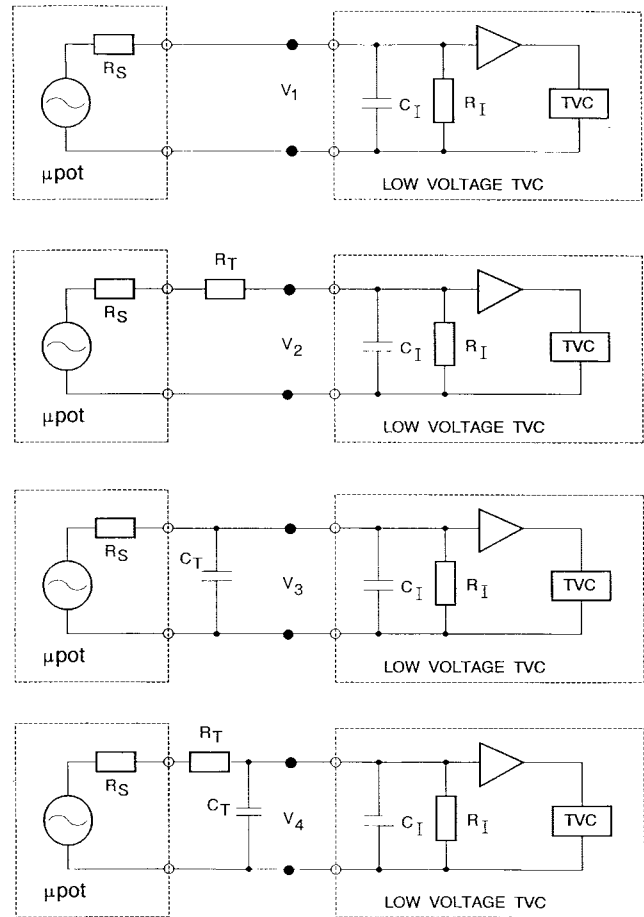


Fig. 4. Four measurements needed to compute C_I and R_I using the insertion method.

For example, using values of R_I for the 220 mV range from Fig. 3 and a source resistance $R_S = 50 \Omega$, E_1 will be approximately 30 μ V/V at 100 kHz compared to 300 μ V/V at 1 MHz.

In a more rigorous analysis, the input capacitance C_I of the low-voltage TVC must be considered. This parameter can also be measured using an LCR meter. The loading error E_2 , described in terms of R_I , C_I , the output resistance of the μ pot R_S and the angular frequency ω is

$$E_2 = \{R_I^2 / [(R_S + R_I)^2 + (\omega C_I R_I R_S)^2]\}^{1/2} - 1. \quad (2)$$

To verify the LCR meter measurements of the active input impedance of the low-voltage TVC, a technique was developed that uses passive components inserted into the measurement circuit to determine the input impedance parameters. In this *insertion method*, a small resistance R_T is connected in series between the μ pot and the low-voltage TVC, and a small capacitance C_T is connected across the input of the low-voltage TVC. Measurements are made in the four different configurations shown in Fig. 4, and a mathematical model (see the Appendix) is used to determine the input resistance R_I and input capacitance C_I of the low-voltage TVC. The values of R_T and C_T were measured using the LCR meter and found to change less than 2% over the 100 kHz to 1 MHz frequency range, so the 100 kHz values were used in the calculation.

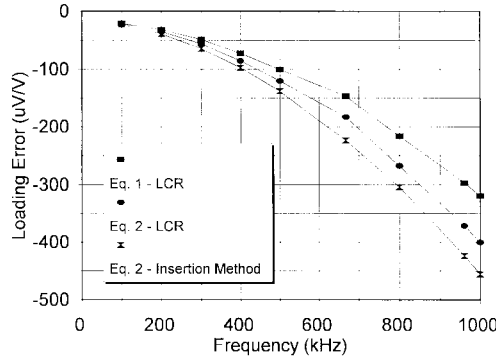


Fig. 5. Difference in the loading errors ($R_S = 50 \Omega$) using LCR meter resistance data with (1), LCR meter resistance and capacitance data with (2), and insertion method data with (2).

TABLE I
MINIMUM (100 Hz) AND MAXIMUM (1 MHz) EXPANDED
UNCERTAINTIES (IN $\mu\text{V/V}$) ASSIGNED TO THE LOW-VOLTAGE TVC
USING THE 250-mV TVC AND THE μpot STEP-DOWN PROCEDURE

Voltage	200 mV	100 mV	50 mV	20 mV	10 mV	5 mV	2 mV
100 Hz	14	16	30	50	60	190	270
1 MHz	150	170	270	320	340	450	600

For a 50Ω source resistance, the differences in the loading errors computed by (1)–LCR (R_I measured using an LCR meter), (2)–LCR (R_I and C_I measured using an LCR meter), and (2)–Model (R_I and C_I measured using the insertion method) are shown in Fig. 5. It is apparent that the input capacitance C_I , which is on the order of 50 pF over the entire frequency range, has a significant influence, and (2) should be used to compute the loading errors. The agreement between the error curves computed using (2) is well within the expanded uncertainties of the ac–dc difference of the reference TVC, so either method may be used to compute these errors.

IV. LOW-VOLTAGE UNCERTAINTIES

Correcting for loading errors based on (2), two step-down procedures were used to determine the ac–dc difference of a low-voltage TVC used as a working standard at NIST. The first procedure employed a set of μpots that have source impedances that range from 2Ω to 40Ω . The second used a set of 50Ω rf attenuators. The differences between the two procedures in assigning ac–dc differences to the low-voltage TVC are well within the present expanded uncertainties. These figures ($k = 2$) for each voltage level, are given in Table I.

V. CONCLUSIONS

The low-voltage step-down techniques described briefly in this paper were developed to support the calibration of low-voltage TVC's, μpots , DVM's, DMM's, and multifunction calibrators. The techniques employ a characterized 250-mV TVC as a starting reference for ac–dc difference, followed by μpots , and resistive attenuators to define voltages between 2 mV and 200 mV. Because μpots and attenuators have nonzero output impedances, a knowledge of the input impedance of the measuring device is critical. Commercial DVM's and

DMM's were found to have even larger decreases in input impedance versus frequency. Normally, an LCR meter is adequate to measure the impedance parameters; however, it is important to verify the performance of the LCR meter, particularly above 100 kHz. To accomplish this, an insertion method was developed, in which passive components are inserted in series with and in parallel to the measured voltage, and a model is used to analyze the measurements and calculate the input impedance parameters needed to determine the loading errors. Correcting for these loading errors has led to better agreement between step-down procedures with different source impedances, and it should ultimately lead to smaller uncertainties for low-voltage standards.

APPENDIX

The insertion method consists of four low-voltage TVC measurements at the frequency of interest. The parameters needed to derive values for R_I and C_I are $R_S, R_T, C_T, V_1, V_2, V_3, V_4$ (from Fig. 4)

$$V_1 = \frac{\frac{R_I}{1 + j\omega C_I R_I}}{R_S + \frac{R_I}{1 + j\omega C_I R_I}} V_S;$$

$$V_2 = \frac{\frac{R_I}{1 + j\omega C_I R_I}}{R_S + R_T + \frac{R_I}{1 + j\omega C_I R_I}} V_S;$$

$$V_3 = \frac{\frac{R_I}{1 + j\omega(C_I + C_T)R_I}}{R_S + \frac{R_I}{1 + j\omega(C_I + C_T)R_I}} V_S;$$

$$V_4 = \frac{\frac{R_I}{1 + j\omega(C_I + C_T)R_I}}{R_S + R_T + \frac{R_I}{1 + j\omega(C_I + C_T)R_I}} V_S.$$

Setting $a = V_1/V_2$ and $b = V_3/V_4$, two equations can be derived from the voltage equations

$$C_I = \frac{1}{\omega R_I} \sqrt{\frac{a^2(R_S + R_I)^2 - (R_S + R_T + R_I)^2}{(R_S + R_T)^2 - a^2 R_S^2}} \quad (\text{A1})$$

$$C_I + C_T = \frac{1}{\omega R_I} \sqrt{\frac{b^2(R_S + R_I)^2 - (R_S + R_T + R_I)^2}{(R_S + R_T)^2 - b^2 R_S^2}}. \quad (\text{A2})$$

Equations (A1) and (A2) can be combined to find the value for resistance R_I .

$$\sqrt{\frac{a^2(R_S + R_I)^2 - (R_S + R_T + R_I)^2}{(R_S + R_T)^2 - a^2 R_S^2}} + \omega R_I C_T - \sqrt{\frac{b^2(R_S + R_I)^2 - (R_S + R_T + R_I)^2}{(R_S + R_T)^2 - b^2 R_S^2}} = \text{residue}. \quad (\text{A3})$$

A least-squares algorithm was used with (A3) at each frequency to find the R_I value corresponding to a minimum

residue. After the R_I at each frequency is determined, (A1) is used to compute the corresponding C_I . Once the values for R_I and C_I are obtained, the loading error E can be defined as

$$E = \frac{V_M - V_S}{V_S} = \frac{V_M}{V_S} - 1$$

$$= \sqrt{\frac{R_I^2}{(R_S + R_I)^2 + (wC_I R_I R_S)^2}} - 1$$

where V_S is the actual applied voltage and V_M is the voltage measured using the μ pot or TVC.

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Nile M. Oldham, (M'73–SM'92) for a photograph and biography, see this issue, p. 355.

S. Avramov-Zamurovic, for a photograph and biography, see this issue, p. 355.

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